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METHODOLOGY REPORT

AIR DISTRIBUTION IN PROTECTIVE SHELTERS

By

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1. Subject report is approved.

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During tests of a chemical and/or biological protective shelter, concentration measurements are usually made within the shelter to determine if a contaminant can infiltrate from the outside and/or ensure that the shelter's filtration system is effectively removing any contaminant released within it. A Test Operations Procedure (TOP) is needed to provide guidance on where to sample for the highest contaminant concentrations within a protective shelter. Development of this TOP requires a mathematical model that can describe the air circulations within enclosures and the resulting contaminant distributions. Little information is available on the turbulence-driven diffusion processes within enclosures. Factors such as a biological receptor's intermittent exposure to high concentrations of toxic vapors and the resulting nonlinear physiological response must be considered during model development. Capabilities of available indoor air quality and fluid dynamics models are reviewed, and recently developed fast-response gas concentration and turbulence measuring instruments are tested in an enclosure. It is recommended that a working group consisting of both modelers and experimentalists be formed to address TOP modeling and measurement requirements.

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FOREWORD

This report describes work accomplished under U.S. Army Test and Evaluation Command (TECOM) Methodology Project No. 8-CO-M93-DPD-007. Dr. Christopher Jones of the United Kingdom Chemical/Biological Defence Establishment (CBDE), Porton, England and Dr. Helen Higson of the University of Manchester Institute of Science and Technology (UMIST), Manchester, England performed the tracer gas concentration measurements. Dr. Joseph Klewicki and Mr. Erik Kelner of the University of Utah Mechanical Engineering Department performed the hot-wire anemometer measurements. Dr. Eugene Yee of the Canadian Defence Research Establishment, Suffield contributed useful discussions and copies of several technical papers referenced in this report. Mrs. Susan Gross provided word processing support for this project.

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SECTION 1. SUMMARY

1.1 BACKGROUND

Air distributions within enclosures designed for human occupation have recently become a subject of increased interest for both the military and civilian sectors of society. Military interest is focused on the protection of soldiers during attacks with chemical and/or biological weapons (e.g., Bauer, 1991; Grim and Gandhi, 1988). Civilian interest includes a range of indoor air-quality issues such as chemical outgassing from the interior contents of buildings, transport and deposition of dust or radon decay products, and routine workplace chemical exposure. Of common interest to both the military and civilian sectors is the need to assess the physiological effects of unexpected atmospheric contaminants following their infiltration into or explosive release within an enclosure. A common thread for these various interests is the need to define methodologies for measuring and modeling the infiltration, distribution, and deposition/resuspension of contaminants within an enclosure or protective shelter. A fundamental problem in meeting this need is that, while indoor air quality assessments are routinely made using gross measures of properties such as the air exchange rate, there is little information available on the microscale processes that control contaminant concentration distributions within enclosures.

1.2 PROBLEM

During tests of a chemical and/or biological protective shelter, concentration or dosage (time-integrated concentration) measurements are usually made within the shelter to determine if a contaminant can infiltrate from the outside. Also, internal concentration or dosage measurements are sometimes made to ensure that the shelter's filtration system is effectively removing any contaminant released within it. Although it is intuitively obvious that a shelter may contain areas where the air circulation is stagnant and an air contaminant can accumulate, it is impractical to make concentration or dosage measurements throughout its entire volume. A Test Operations Procedure (TOP) is therefore needed to provide guidance on where to sample for the highest contaminant concentrations within a protective shelter. The development of this TOP requires a mathematical model that can describe the air circulations within enclosed shelters and the resulting air contaminant distributions.

The development of a model that can predict air and contaminant distributions within a protective shelter is conceptually similar to the development of an atmospheric diffusion model that uses numerical techniques to solve the equations of motion and conservation in order to predict atmospheric circulations, turbulence, and the distribution of airborne pollutants. However, the development of a model for a protective shelter is hampered by deficiencies in both measurements and modeling. The measurement deficiencies are twofold. First, contaminant infiltration into and distribution through an enclosure are determined by air movements on velocity scales that are not readily measured using conventional instrumentation. Conventional anemometers are designed to measure velocities on the order of several meters per second, while air movements within enclosed spaces are typically on the order of a few centimeters per second. Second, conventional flow measurement and contaminant sampling

instruments have insufficient frequency response to resolve the microscale turbulence and flow fields within enclosures and the resulting contaminant concentration variations. As might be expected from the measurement deficiencies, the indoor modeling deficiencies include an inadequate capability to characterize air flow and contaminant concentration distributions within enclosures.

1.3 OBJECTIVE

The objective of this methodology investigation was to identify the measurements and model inputs most relevant to the modeling of airborne contaminant distributions within protective shelters.

1.4 PROCEDURES

As a first step, we conducted a literature search to define models and measurement methodologies appropriate for indoor air quality studies. We also contacted our colleagues at the Chemical/Biological Defence Establishment (CBDE)-Porton, England, and the Defence Research Establishment Suffield (DRES), Canada and found that they shared our interest in the protective shelter air and contaminant distribution problem. Consequently, we expanded the scope of a tripartite concentration fluctuation test program scheduled at U.S. Army Dugway Proving Ground (DPG) for May 1993 to include measurements pertinent to protective shelter issues. The expanded measurement program included the use of fast-response tracer gas detectors independently developed by CBDE and DRES and a fast-response hot-wire anemometer developed by the University of Utah Mechanical Engineering Department. The hot-wire anemometer is capable of providing the fast-response, high-resolution flow measurements needed to characterize air flow and turbulence in a protective shelter. A series of trials were conducted at the DPG Tower Grid Command Post (CP) building to investigate infiltration of a tracer gas into the CP and the turbulence and tracer concentration distributions within it. The objective of these trials was to demonstrate a methodology for making the fast-response turbulence and concentration measurements needed to characterize and model air contaminant distributions within protective shelters.

1.5 RESULTS

The Tower Grid CP infiltration trials showed that a closed, but unsealed (leaky) enclosure of conventional cinder block design can provide considerable infiltration delay and protection against the intrusion of windborne contaminants. The tracer concentration distribution in the back (north) room of the CP building was non-uniform and dependent upon microscale turbulence and convection generated by differential heating and chimney effects. A report on these and other tracer concentration measurements is currently being prepared under contract to CBDE by the University of Manchester Institute of Science and Technology (UMIST).

The hot-wire anemometers measured uneven distributions of low-speed flows and turbulence within the CP building. Human activity (people standing and moving around in the north room of the CP building) increased the turbulence intensities by a factor of 5 to 10 over those measured when this room was

vacated. Also, the turbulence intensities measured near windows and external walls exceeded the turbulence intensities in the center of the room by a factor of 10. However, the largest turbulence intensities measured inside the CP enclosure were a factor of 100 or more less than the turbulence intensities measured in the ambient air outside the CP.

1.6 CONCLUSIONS

It would be premature to develop a TOP for defining air and contaminant distributions within a protective shelter at this time. The required TOP should specify a model for predicting airborne contaminant distributions within enclosures and the measurements needed to obtain the model's inputs. However, the available indoor air quality models, which are based on the assumption of instantaneous uniform mixing or Gaussian contaminant distributions, are inadequate for defining optimum sampling locations in enclosures. The Tower Grid CP trials clearly demonstrate that the uniform mixing assumption is at variance with reality, especially for short sampling times. The nonuniform distribution of airborne contaminants is particularly significant because the toxic load experienced by enclosure occupants is a nonlinear function of concentration; an enclosure occupant's intermittent encounter with a high concentration of an unevenly mixed contaminant could greatly exceed the toxic load due to continuous exposure to the same amount of contaminant uniformly distributed within the enclosure. TOP preparation should await the development of a model that can predict sufficiently realistic flow, turbulence, and contaminant distributions to define sampler locations for an enclosure vulnerability test program. Several fluid dynamics models have been identified that might be suitable for this purpose, but the utility of these models requires further investigation. Modeling and simulation can complement, but are unlikely to replace measurements until they can reliably replicate the statistics describing time-dependent fluid flow problems.

A substantial measurement program is needed to define the statistics of flow and contaminant distributions within an enclosure. The measurements should be made with instruments capable of resolving sufficiently fine temporal and spatial scales that sufficient statistical information is available for toxic load factor modeling. The high-resolution, fast-response instruments evaluated in this methodology investigation meet these measurement requirements. In particular, this methodology investigation has shown that: (1) the fast-response concentration detectors developed by the UK and Canada are suitable for application to indoor air contaminant distribution issues, and (2) fast-response hot-wire anemometers are capable of resolving the temporal and spatial scales of flows and turbulence within enclosures.

1.7 RECOMMENDATIONS

Enclosure air circulation and contaminant measurements and model development should proceed simultaneously. Better models become possible as measurements improve, and improved modeling stimulates improvements in measurement technology. A working group, consisting of both modelers and experimentalists, should be formed to address the dual problems of measurements and modeling. TOP development can begin once a fluid dynamics model is identified

that can define air circulations and air contaminant distributions within enclosures.

Fast-response hot-wire anemometers and sophisticated fluid dynamics models are needed to define the low-velocity flow and turbulence characteristics of air in protective shelters. Proper use of these technologies requires specialized training in computational fluid dynamics. At least initially, it likely would be more cost effective to acquire this specialized expertise through contractor assistance than to develop it in-house.

Fast-response concentration sensors have significant applications for chamber and outdoor field testing as well as for protective shelter testing. Recent advances in photoionization detector technology make fast-response detection of many airborne organic contaminants achievable, and anticipated improvements in ultraviolet lamp stability (UMIST Professor Richard Griffiths, personal communication, 1993) enhance the attractiveness of an investment in this technology. DPG acquisition of this technology for airborne tracer studies and contaminant sampling is recommended.

The need to describe air contaminant distributions within enclosed shelters is not an isolated or uniquely military problem. Because people spend up to 90 percent of their lives indoors (Austin et al., 1992), indoor air quality is a major concern for state and federal occupational safety and health agencies. Contaminant distributions within shelters are also a growing concern for allied ministries of defense; the British and Canadians have been particularly active in this area. With the recent advances in fast-response measurement technology and growing interest in indoor air quality issues, rapid advances in indoor air quality characterization may be possible through interagency and international cooperation.

SECTION 2. DETAILS OF THE INVESTIGATION

2.1 INTRODUCTION

As with most complex problems, an understanding of airborne contaminant distributions within enclosures must be gained through modeling. Data gathered during an airborne contaminant event are either parameterized or converted to statistical information for model input. The model is then used to generate knowledge or understanding of that event. Because there is always more happening than can be captured as data, some information is always lost during processing into statistical summaries or the parameterizations required for model input. Also, modeling assumptions can never completely replicate all aspects of an event's physics. It is therefore of paramount importance to define the most significant data points to be captured, the most pertinent statistics or parameterizations to be formed, and the most relevant physics to be included in the model prior to development of an airborne contaminant distribution TOP for protective shelters. This report compares measurement and modeling requirements with available measurement and modeling technologies as the first step in the development of a protective shelter TOP.

2.2 INDOOR CIRCULATIONS AND CONCENTRATION DISTRIBUTIONS

The release of airborne contaminants into an atmosphere (whether indoor or ambient) creates a concentration gradient. The distribution of this contaminant then becomes a function of the atmosphere's flow and turbulence. The flow tends to deform the shape of the initial contaminant cloud and transport it away from its origin, while turbulence causes mixing with the other constituents of the indoor or ambient air. Other factors affecting airborne contaminant distributions include interactions with boundaries such as deposition, resuspension, and outgassing. For indoor atmospheres, the air exchange rate between the enclosure and its surroundings acts as an additional source or sink term for airborne contaminants.

Flows within an enclosure result from a combination of: (1) buoyancy-driven convective circulations generated by differential heating of enclosure surfaces, and (2) forced circulations produced by ventilation, infiltration, mechanical air movement, or other movement within the enclosure. Indoor convective circulations, which tend to be slow (on the order of 1 to 10 cm/s), are caused by warm air rising from heated surfaces and a comparable mass of cooler air sinking. Convective circulations arise when buoyancy (the product of the gravitational acceleration g, coefficient of thermal expansion β, and differential heating ΔT) overcomes opposing inertial and frictional forces. Natural convection within an enclosure can be parameterized using the Grashof number Gr or the Rayleigh number Ra. The Grashof number is given by

$$Gr = g\beta\Delta TL/\nu^2 , \qquad (2\text{-}1)$$

where L is a characteristic length and ν is the kinematic viscosity of air. The Rayleigh number is given by

$$Ra = g\beta\Delta TL^3/\alpha\nu\,, \qquad (2\text{-}2)$$

where α is the thermal diffusivity of air. Karac et al. (1985) argue that the Grashof number is an unimportant scaling parameter and define a critical value of the Rayleigh Number (Ra_c = 1700) for the onset of convection. Others, notably Brager and Revzan (1991), use a critical Grashof number to define the onset of convection.

The buoyant and mechanical forces that drive atmospheric motions also create a broad spectrum of turbulent eddies. The energy within these eddies is continuously partitioned into progressively smaller eddies until the scales of motion are so small (on the order of 1 mm) that air viscosity effects become significant; the energy eventually dissipates in molecular motion as heat. Because the air within enclosures does not have access to a continuous resupply of larger scale eddies, the spectrum of eddy motion is severely truncated at the larger (longer wavelength) scales unless supplemented by the energy content of forced circulations. This distribution of energy across the spectrum of motion defines the rate at which airborne contaminants are transported and mixed.

In the absence of strong forced circulations, the diffusive power of air within an enclosure can be many orders of magnitude lower than the diffusive power of outside air. The spectra in Figure 1, which were obtained from measurements in the DPG Tower Grid CP building, illustrate differences between the ambient and indoor turbulence levels measured by hot-wire anemometers. This figure compares the spectrum of ambient turbulent energy as a function of frequency (solid line) with the spectra of turbulence measured at two locations within the Tower Grid CP building (dashed lines). The spectrum for ambient air contains three to four orders of magnitude more power than the spectra for indoor air. Also, the spectrum from a position near the CP building window (heavy dashed line), where infiltration and convection were present, exceeds the spectrum for still air in the building center (light dashed line) by two orders of magnitude. The prominent spikes at 60 Hz in the still air spectra suggest that the measurements were made near the noise level for the hot-wire system. The effects of the difference in diffusive power between indoor and outdoor air has been experienced by anyone who has chopped onions in an unventilated kitchen and suffered eye discomfort. Moving the onion chopping operation outside, even in calm conditions, can alleviate the discomfort because of the greater diffusion in ambient air.

The concentration of a contaminant released within an unventilated enclosure will diminish very slowly if acted on only by slow convection and molecular diffusion (the net transport of the contaminant across a concentration gradient by random Brownian motion). This slow dilution rate is a major reason why building occupants are often at greater risk from inhalation of toxic vapors than from burns during a fire. The prevalence of these slow mixing processes calls into question the common indoor air quality model assumption that uniform mixing of airborne contaminants is rapidly achieved within enclosures.

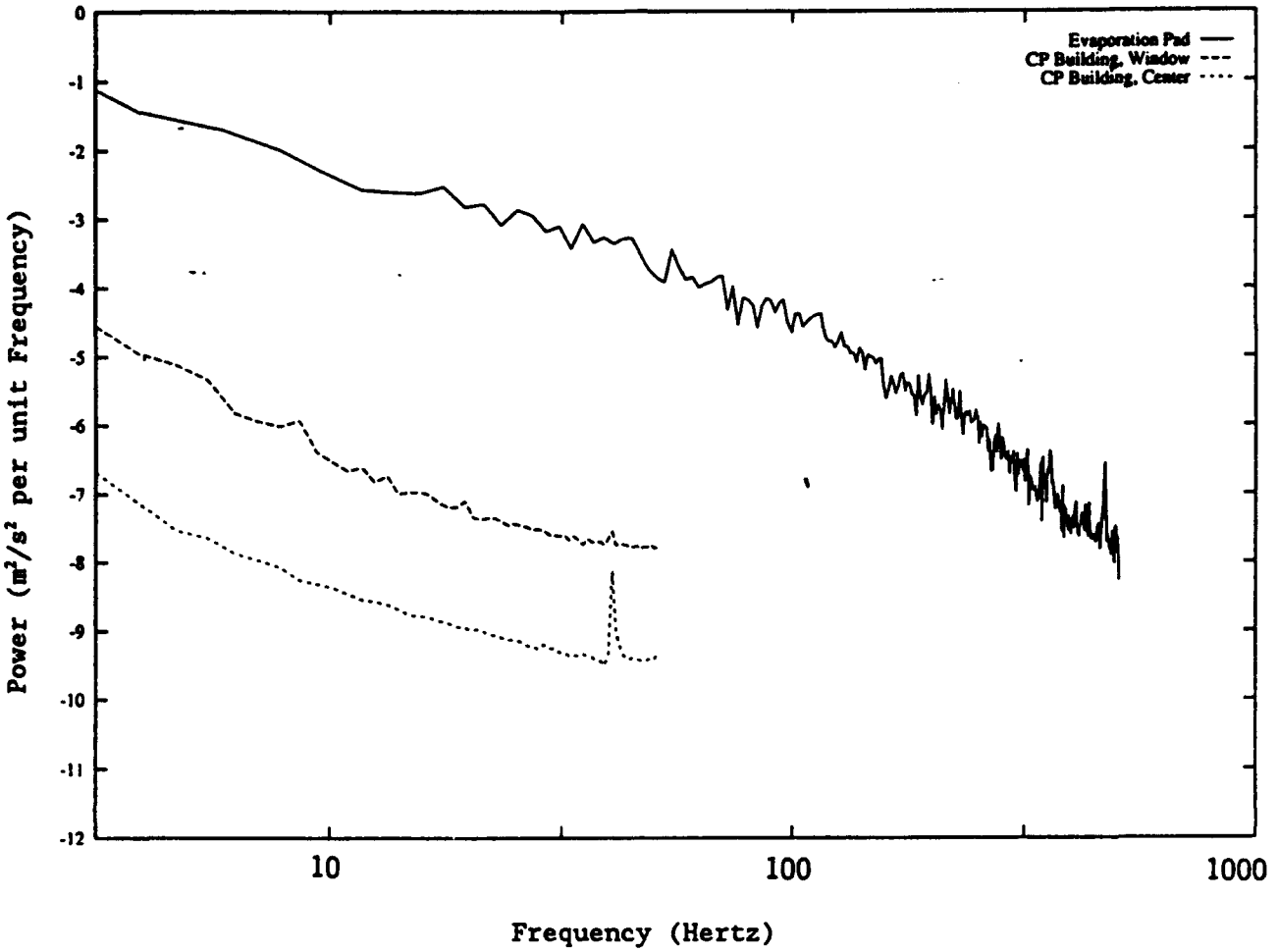

Figure 1. Spectra for ambient air (solid line) and the CP building interior window (heavy dashed line) and room center (light dashed line) (courtesy of the University of Utah Department of Mechanical Engineering). Note that logarithmic scales are used on both axes.

Forced circu tions within an enclosure (typical flows of several tens of centimeters per second) are usually attributable to outside air blowing into enclosure openings or forced-air heating/cooling systems. Unlike convective circulations that originate along a wall and move vertically along the wall, forced circulations usually enter the enclosure at small, discrete locations (open windows, ducts, etc.) and flow toward its interior. Forced circulations are commonly parameterized by the number of air changes per hour (ach), which is the ratio of the infiltration flow rate (volume per hour) to the interior shelter volume.

As shown in Figure 1, the indoor turbulence level resulting from forced circulations is considerably greater than the level produced by natural convection. This difference is explained by the fact that air enters an

enclosure as a jet with some initial velocity. The jet immediately encounters and begins to entrain indoor air, and its velocity decreases as its momentum is converted to turbulent motions. The region within an enclosure that is affected by a forced circulation depends on the enclosure geometry and air change rate. Interior air at some distance from the incoming air is often unaffected by the forced circulation. Contaminant concentrations in these stagnant zones are governed by local concentration gradients and molecular diffusion. An exception occurs when the incoming ambient air is 5 °C or more cooler than the indoor air. A forced air exchange with this temperature differential can produce a density stratification in which the warm indoor air is displaced by the cooler outdoor air (Wilson, 1990). If the forced ventilation rate is sufficiently high to prevent warming of the infiltrating air, the dead air space can be completely displaced and the contamination level within the entire enclosure can approach that of the ambient air.

Until recently, little information has been available on the statistical properties of the concentrations of contaminants released into the atmosphere. Because only time-mean concentration measurements have been available, these measurements generally have been accepted as sufficient for monitoring hazardous contaminants in the atmosphere. Similarly, the current atmospheric diffusion models, which predict ensemble-mean concentrations, have been assumed to be sufficient for assessing the hazards of airborne contaminants. However, within the last decade a growing body of experimental results (Fackrell and Robins, 1982; Mylne and Mason, 1991; Yee et al., 1993a and b) has provided convincing evidence that time- and ensemble-mean concentrations do not adequately represent the hazards presented by airborne contaminants. Fast-response ambient concentration measurements are now being used to develop models that predict near-instantaneous concentration probability distribution functions in addition to ensemble-mean concentrations. No similar contaminant concentration distribution statistics are available for indoor air. The absence of these statistics is a serious impediment to the development of indoor air quality models.

2.3 DOSAGE, DOSEMENT, AND TOXIC LOAD

Occupational exposure limits for atmospheric contaminants are usually presented in terms of some dosage or mean concentration-exposure time product that should not be exceeded. Common exposure limits include:

IDLH -- Immediately Dangerous to Life or Health. The maximum contaminant level from which one could escape within 30 min without experiencing any escape-imparing symptoms or irreversible health effects (National Institute of Occupational Safety and Health/Occupational Safety and Health Administration, 1978).

TLV/TWA -- Threshold Limit Value/Time Weighted Average. The time-weighted average concentration for a normal 8-h workday and 40-h work week to which nearly all workers may be repeatedly exposed without adverse effect (American Conference of Governmental Industrial Hygienists, 1988)

TLV/STEL -- Threshold Limit Value/Short Term Exposure Limit. The concentration to which workers can be exposed continuously for a short (15-min) period without suffering from various ill effects (American Conference of Governmental Industrial Hygienists, 1988).

Exposure limits presented in the above terms contain the implicit assumptions that: (1) the concentration level remains constant, and (2) human physiological response to exposure is linearly related to the average concentration over the specified exposure time. These assumptions may be suitable when the contaminant is well mixed. However, contaminant exposure is often intermittent and concentration levels can be highly variable. The need to account for varying concentration levels led to a definition of dosage D as the time-integral of concentration χ over total exposure time t_e, or

$$D = \int_0^{t_e} \chi(t)\, dt \qquad (2\text{-}3)$$

where the typical units for dosage are milligram-minutes per cubic meter. Although this dosage representation accounts for intermittent exposure to variable concentrations, it still assumes that there is a linear relationship between dosage and physiological response.

The nonlinear interrelationship between nerve agent concentration, exposure time, and physiological response has been recognized for many years. The 2-min equivalent dosage used by the D2PC chemical hazard prediction model (Whitacre et al., 1987) is an attempt to account for this nonlinear interrelationship. For a given physiological response (e.g., 50 percent of exposed individuals die), the 2-min equivalent dosage D_{2e} for exposure time t_e greater than 2 min is given by

$$D_{2e} = D_2 \left(\frac{t_e}{2}\right)^b \; ; \; t_e \text{ (min)} \geq 2 \text{ min}, \qquad (2\text{-}4)$$

where D_2 is the 2-min dosage that produces the specified physiological response and b is an empirical constant (0.274). The fact that dosages for exposure times longer than 2 min are referenced to physiological response for a 2-min exposure time should not be interpreted as indicating a linear dosage-response relationship for exposure times of less than 2 min. Rather, 2 min was the shortest practical sampling period at the time when the data upon which Equation (2-4) is based were acquired.

In summarizing their reviews of fundamental research on the effects of exposure to toxic gases, Ride (1984) and Griffiths and Megson (1984) note that, for a given dosage, intermittent exposure to high concentrations tends to produce more severe toxic effects than more frequent exposure to lower concentrations. To accommodate this effect, Ride (1984) introduces the concept of dosement

$$Do = \int_{o}^{t_e} \chi^n (t)\, dt \quad , \quad n>1 \tag{2-5}$$

where the exponent n in this modified dosage equation is greater than unity. Ride (1984) also notes that the exponent n is constant over a wide range of concentrations and exposure times for many substances. In related work, Griffiths and Megson (1984) use a probit model (Finney, 1971) to derive a simple mathematical expression that illustrates how the toxic effect can increase with intermittency when dosage is held constant and n is greater than unity. (They define intermittency as the fraction of time that the concentration measured at a receptor falls below a specified threshold level.)

Ride (1984) presents the framework for a model of a fluctuating gas concentration field in which the variability of concentrations at a receptor is parameterized by $\sigma_\tau/\langle\chi\rangle$, where σ_τ is the standard deviation of concentrations measured with time resolution τ and $\langle\chi\rangle$ is the time-mean concentration. This model defines the dosement resulting from fluctuating concentrations as

$$D_o = \left[\langle\chi\rangle^n\, t_e\right]\left[\kappa\,(\sigma_\tau/\langle\chi\rangle)^\lambda + 1\right]^{n-1} , \tag{2-6}$$

where κ and λ are empirical constants. Comparison of Equations (2-5) and (2-6) shows that the dosement for exposure to variable concentrations is equal to the product of the dosement for exposure to the time-mean concentration and an enhancement factor which increases as the intensity of concentration fluctuations increases.

Further development of the Ride (1984) model might include improvement of both the enhancement factor term and dosement definition. For example, recently acquired turbulence and concentration fluctuations statistics (e.g., Yee et al., 1993a and b) might serve as a basis for further work on the enhancement term. Ride (1984) also acknowledges that the toxic enhancement factor becomes unrealistically large for large values of n and high fluctuation intensities. This limitation could be reduced through use of a reference concentration χ_o, converting the dosement equation to

$$Do = \int_{o}^{t_e} \left[\frac{\chi_{(t)}}{\chi_o}\right]^n \chi_o\, dt \tag{2-7}$$

This modification would also have the desirable effect of providing dosement with units equivalent to those used for dosage.

The toxicological literature includes the concept of a "toxic load" which is very similar to Ride's (1984) dosement. Toxicological studies of common

industrial gases (Withers and Lees, 1985; ten Berge, 1986) indicate that when data points representing a specific physiological response threshold are plotted on logarithmic scales of concentration versus exposure time, a straight line is found over a wide range of exposure times. This observation suggests that a toxic load can be represented by the simple expression

$$L = \left[\left(\frac{\chi}{\chi_o} \right)^n \chi_o \right] t_e \qquad (2\text{-}8)$$

where the exponent n is the slope of the straight line on log-log paper. In his review of the literature for 20 industrial gases, ten Berge (1986) finds that the exponent n ranges from 0.8 to 3.5, depending on the gas. The toxic load concept is now used by the Health and Safety Executive of Great Britain for assessments of the hazards of exposure to toxic gases (Fairhurst and Turner, 1993).

In summary, the nonlinear physiological response to atmospheric contaminants implies that: (1) gross time-averaged exposure estimates are inadequate for hazard assessment, and (2) temporal and spatial scales of concentration distribution measurements should be at least as fine as the response of the biological receptor. Wilson (1990) observes that atmospheric concentration levels, toxic load variations, and biological system susceptibilities all tend to follow log-normal distributions. Because the median rather than the mean is the most important measure of central tendency for a log-normal distribution, time-mean concentration measurements cannot fully describe the hazard presented by an atmospheric contaminant.

2.4 INDOOR AIR QUALITY AND FLUID DYNAMICS MODELS

A model capable of describing air and contaminant distributions within protective shelters is needed for two reasons. First, given a set of enclosure characteristics, a model is needed to assist the test director in determining the optimum sampling locations to satisfy the test objectives. Second, given an adequate set of measurements, a model is needed to describe the air distribution and contaminant concentration-time history throughout the enclosure in sufficient detail to permit computation of toxic loads which can be related to physiological response. Our literature survey of available indoor air quality models indicates that no current model is capable of performing these functions, although some progress has been made in addressing certain indoor air quality issues.

Current indoor air quality models have several major limitations. The primary limitation of all known indoor air quality models is their physically unrealistic assumption of uniform contaminant mixing throughout the active indoor air space. This uniform mixing assumption is shared by current Army nuclear, chemical, and biological (NBC) protection and decontamination assessment procedures (for example, Salomon et al., 1988). The temporal and spatial variations in flow and contaminant concentration distributions are so complex that simple volume averages cannot express actual exposures. Each of

the indoor air quality models we reviewed also appears to be designed for a limited range of contaminants, initial conditions, and enclosure geometries.

An indoor air quality model that takes a tentative step towards addressing the microscale flow within an enclosure is the RADTRAN model of Brager et al. (1991). RADTRAN is designed to predict the transport and deposition of radon and its decay products. The model includes convective heat transfer equations that simulate both natural and forced convection for combinations of obstacles, apertures, and heat and momentum sources for a 2-dimensional rectangular enclosure. RADTRAN also calculates an air contaminant mass transfer coefficient (deposition velocity) to enclosure surfaces. This deposition velocity is based on the near-surface flow characteristics and contaminant concentration gradient. Buoyancy-driven enclosure flow is parameterized by the Grashof number. As might be expected, the near-surface convective motions have a significant effect on deposition rates; the model results indicate that deposition in a turbulent flow is much greater than in a laminar flow (Brager and Revzan, 1991).

Limitations of the RADTRAN model include its assumption of uniform mixing within the enclosure (an assumption that is probably not serious for an ubiquitous contaminant such as radon) and its limited ability to characterize existing flows in real enclosures. Also, RADTRAN does not address the effects of electrophoretic or thermophoretic forces on deposition. The contributions of electric and thermal forces to deposition may be important, depending on the deposition surface's characteristics and environmental factors such as humidity (Nazaroff and Cass, 1987).

Nazaroff and Cass (1989) describe a model that attempts to account for nonuniform contaminant mixing within an enclosure. The enclosure is represented by a set of interconnected chambers, each of which has its own well-mixed contaminant concentration. This multichamber representation of the enclosure explicitly accounts for the effects on the atmospheric aerosol concentration of ventilation, filtration, deposition, direct indoor emission, and coagulation. The aerosol model is also coupled to a model for gaseous contaminants. Although superior to the assumption of uniform mixing over the entire enclosure, the artificial compartmentalization is unlikely to offer realistic solutions to the contaminant concentration distribution problem.

SHELTER-1 (Wilson and Zelt, 1990) is a leading building infiltration model. SHELTER-1 is capable of considering fluctuations in ambient contaminant concentrations, including the intermittency of these concentrations. The model uses a log-normal probability distribution to predict the peak instantaneous concentration and toxic load. The indoor concentration is derived as a function of the outdoor concentration using the inverse of the ventilation rate in air exchanges per hour. A shortcoming of SHELTER-1 is that the contaminants that infiltrate into the enclosure are assumed to rapidly mix with the enclosure air, artificially diminishing indoor concentration variations. Wilson and Zelt (1990) note that the ventilation rate effectively serves as a time constant in a first-order filter that dampens the interior concentration fluctuations.

Austin et al. (1992) review a number of current indoor air quality models. Many of these models are designed for use with a specific contaminant or class of contaminant, and all of them are limited to predictions of time-mean concentrations averaged over the entire enclosure or subcells of the enclosure. Each model tends to have its own unique strengths, limitations, and range of applicability. For example, the SHAPE model (Ott et al., 1988) is designed to predict the frequency of population exposure to indoor air contaminants resulting from various human indoor activities. Other noteworthy models reviewed by Austin et al., (1992) include the Indoor Air Quality Model (IAQM) (Hayes, 1991) and the Contamination Model (CONTAM) (Axley, 1988). IAQM estimates indoor ozone levels for user-selected combinations of environment (home, office, or vehicle), configuration (open windows, air conditioning, etc.), and sources and sinks. CONTAM predicts the interactions (chemical reactions, adsorption, etc.) between an indoor air contaminant and the enclosure's contents.

Computational fluid dynamics (CFD) models are another category of models with the potential for application to the protective shelter airborne contaminant distribution problem. CFD models are typically used to simulate flow, heat exchange, and chemical reactions in and around complex objects such as ducts, manifolds, nozzles, furnaces, valves, circuit boards, air conditioning systems, and pumps. Model output usually consists of a series of steady-state solutions that illustrate the effects of changing input parameters or geometries. CFD models that might be applicable to the protective shelter problem include FIDAP, FLUENT, and BANFF.

The FIDAP fluid dynamics analysis package (Fluid Dynamics International, Inc., Evanston, Illinois) is based on the finite element method, which permits the simulation of flow around objects with complex geometries and boundary conditions. An advantage of a finite element model is that curved surfaces are represented as true curves, not as a series of discrete stair steps. FIDAP is accessed through a Graphical User Interface (GUI) that provides fully interactive control of the program's functions (Adibnazari, 1993). The model is modular and menu driven, allowing the user to select relevant boundary and initialization conditions and a choice of solution methods, material properties, and convergence criteria. One limitation of FIDAP is that it uses only a simple k-ϵ turbulence parameterization that may not adequately represent turbulent dispersion within an enclosure.

The FLUENT CFD model marketed by Fluent, Inc. of Lebanon, New Hampshire accepts complex geometries using a body-fitted coordinate system and a variety of iterative solution methods (Adibnazari, 1993). FLUENT's strength is its wide choice of turbulence representations (including full Reynolds stress solutions) which make it applicable to a wide variety of turbulent flows within complex enclosures. FLUENT can also calculate trajectories and simulate heat transfer, deposition, evaporation, and combustion for particles, droplets, and bubbles dispersed in the flow field. FLUENT features an interactive interface that allows the user to move quickly between the setup, calculation, and post-processing steps.

The JASPER model (Reaction Engineering International, Inc., Salt Lake City, Utah) is designed to simulate flow, heat transfer, and chemical reaction

processes, with particular emphasis on modeling combustion. Typical applications include systems modeling of utility boilers, waste incinerators, and pyrolysis furnaces. JASPER couples turbulent fluid mechanics, gas phase reaction chemistry, radiation, and heat transfer in complex geometries.

All of the above mentioned CFD models offer steady-state solutions, whereas many fluid flow problems have interesting transient or time-dependent solutions. For example, the dispersion of a puff of gas through its mixing volume is a time-dependent process. The KIVA code developed by Los Alamos National Laboratory (and its commercial derivative Turbo Kiva marketed by Cray Research, Inc.) and the TEMPEST code developed by Battelle Pacific Northwest Laboratory offer transient solutions in time steps. However, these codes are costly to run and require a great deal of memory and computational power.

A possible application for CFD models is to identify positions within enclosures where measurements are needed. These models may also suggest which shelter geometries are advantageous or disadvantageous for certain kinds of interior flow and turbulent mixing conditions. Computational fluid dynamics codes are fairly complex and require a user who has sufficient expertise in CFD to properly set up the initial inputs, define the boundary conditions, and interpret the results. These models are also computationally intensive, requiring access to a UNIX-based workstation (or equivalent) as a minimum for efficient operation. Operating licenses for these computer codes are also expensive. None of the CFD codes provide the detailed statistics needed to define dosement or toxic load. These statistics must be obtained from measurements.

2.5 FAST-RESPONSE CONCENTRATION INSTRUMENTS

Existing indoor air quality models are forced into the assumption of uniform mixing in part because of the absence of fine-scale indoor air contaminant concentration measurements. Air contaminant sampling procedures cited in the open literature include the use of gas chromatography, bubblers, and chemical absorbents. These sampling procedures provide total dosage or time-mean concentrations, but no information about short-term concentration fluctuations. Alternative technologies such as flame ionization and photoionization offer the possibility of sufficiently fast response that the statistical characteristics of atmospheric contaminant concentrations can be measured.

The present standard for chemical agent monitoring is the MINICAMS® miniature automatic continuous air monitoring system. (MINICAMS® is a registered trademark of CMS Research Corporation, Birmingham, Alabama.) MINICAMS® functions as an analytical instrument and alarm system primarily for determination of 8-h average concentrations of chemical warfare (CW) agents and their simulants. Major MINICAMS® components include the monitor/controller, sample pump, and compressed gas cylinders and regulators. Air drawn into a MINICAMS® impinges on solid sorbents; collected material is separated by gas chromatography and sampled by combustion using a flame photometric detector (FPD). The MINICAMS® also has a flame ionization detector (FID) option that consists of a wire loop ion collector that intercepts positive ions produced by the burning of organic compounds. Ions impinging on a negatively-biased electrode produce

a small current that is amplified using a FID electrometer circuit. The advantages of the MINICAMS® include its extreme sensitivity (tens of parts per trillion for certain organophosphates) and specificity for CW agents and simulants. Its disadvantages include the high cost, need for skilled operators, requirement for compressed gases (hydrogen, compressed air, and nitrogen), and slow response. With a response time measured in minutes, MINICAMS® is incapable of providing the temporal resolution needed to detect rapid changes in contaminant concentrations within a protective shelter.

One candidate instrument for fast-response concentration measurements is the HRF400 High-Speed Hydrocarbon Analyzer (Cambustion, Ltd., Cambridge, England). Figure 2 shows a tripod-mounted HRF400 sensor. The advantages of the HRF400 include its small size, low flow rate (50 cm^3/min), and fast response time. Like the MINICAMS®, the HRF400 uses a flame ionization technique to ionize combustible products in the air. However, the HRF400 features a unique sampling system that provides a response time near 1000 Hz while retaining a sensitivity on the order of a part per million. The HRF400's disadvantages include the need for compressed gases (hydrogen and air), moderate sensitivity, and cost. The FID process used by the HFR400 is also non-specific; it detects any volatile organic compound (VOC) drawn into the combustion chamber. This inability to distinguish between VOCs could be a disadvantage in a protective shelter where VOCs other than the ones of interest might be present.

Photoionization detection (PID) technology provides an alternative to flame ionization for fast-response concentration measurements. Figure 3 shows a schematic diagram of a PID. Photoionization occurs when air containing an ionizable gas is drawn into the PID and irradiated by an ultraviolet lamp. Gas constituents with ionization potentials lower than the lamp rating are ionized and the resulting ions are collected on charged plates. The small electrical currents (on the order of a picoamp) generated by impact of the ions on the plate can be related through calibration to the ionizable gas concentration. PIDs operating with a lamp rated at 10.6 eV can detect a wide range of VOCs and hazardous gases such as ammonia and hydrogen sulfide. Advantages of PID technology include the relatively low cost, lack of a requirement for supply gases, portability, simple and safe operation, and potential for fast response and good sensitivity. The principal PID disadvantage is the lack of specificity for a particular chemical or chemical group when operated in a complex chemical environment.

Figure 4 shows a recently developed PID, the Total Ionizables Present TIP-SJ2 Fast-Response Concentration Sensor (S&J Engineering, Inc., Scarborough, Ontario, Canada). The TIP-SJ2 is a derivative of the commercially-available Photovac, Inc. TIP® sensor which is used for hand-held gas monitoring. (TIP® is a Trademark of Photovac, Inc., of Thornhill, Ontario, Canada.) The TIP-SJ2 was developed specifically for DRES to measure rapid changes in the concentration field of a dispersing cloud. The TIP-SJ2 is optimized for fast response (frequency response of 270 Hz at the -6 dB point) and offers a sensitivity near 5 parts per billion (ppb) for propylene. The inlet flow rate is 1.5 L/min for the present instrument, but the flow rate and size (37 by 3 cm) could be reduced to approximately half for indoor operation (personal communication with Geoffrey Chandler of S&J Engineering, 1993).

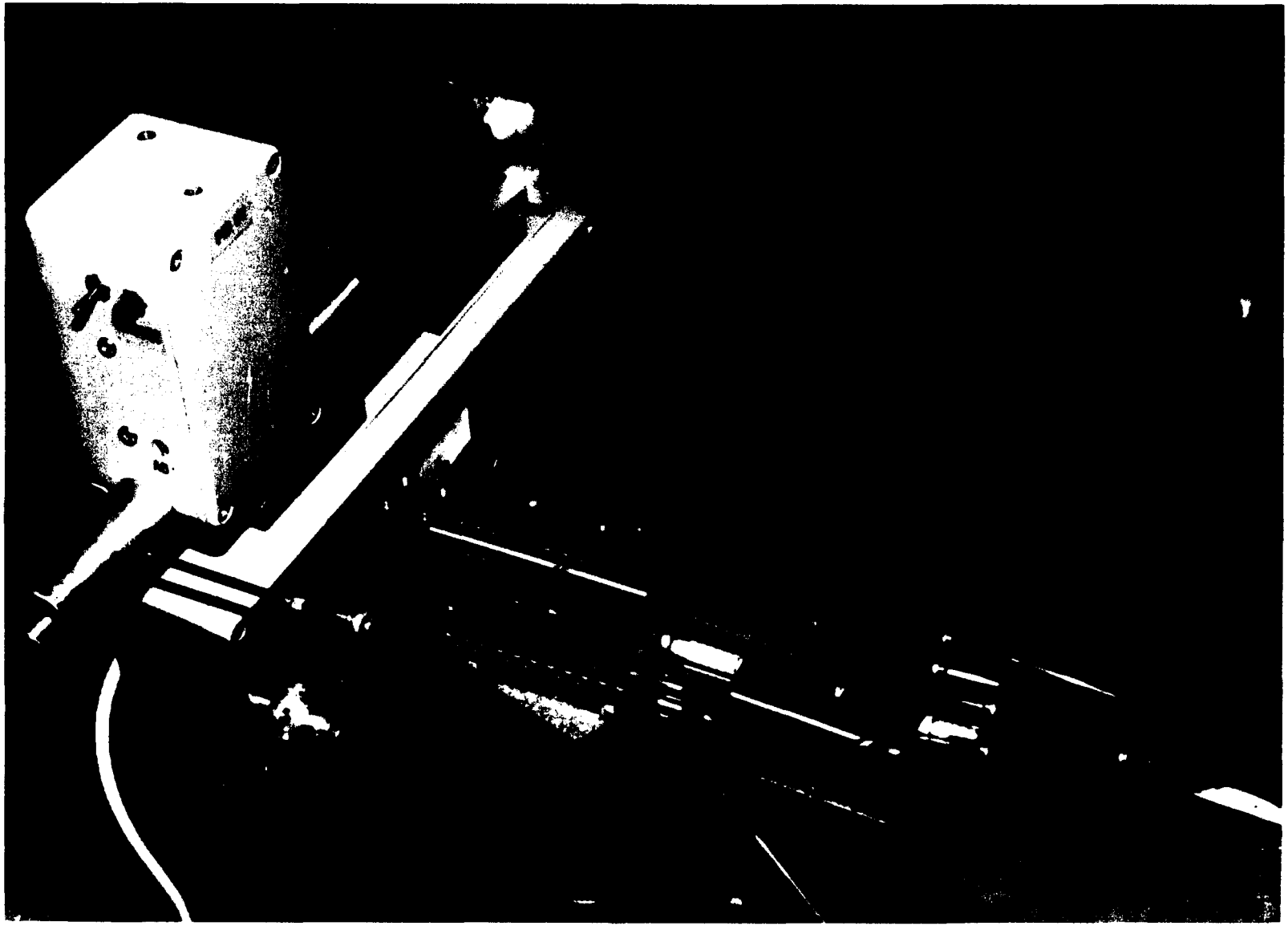

Figure 2. Photograph of the HRF400 Flame Ionization Detector (FID) sensor on a tripod mount (center) with its probe inserted into the intake tube of a prototype Ultraviolet Ion Collector (UVIC). (Photograph by the U.S. Army Dugway Proving Ground Technical Systems Branch.)

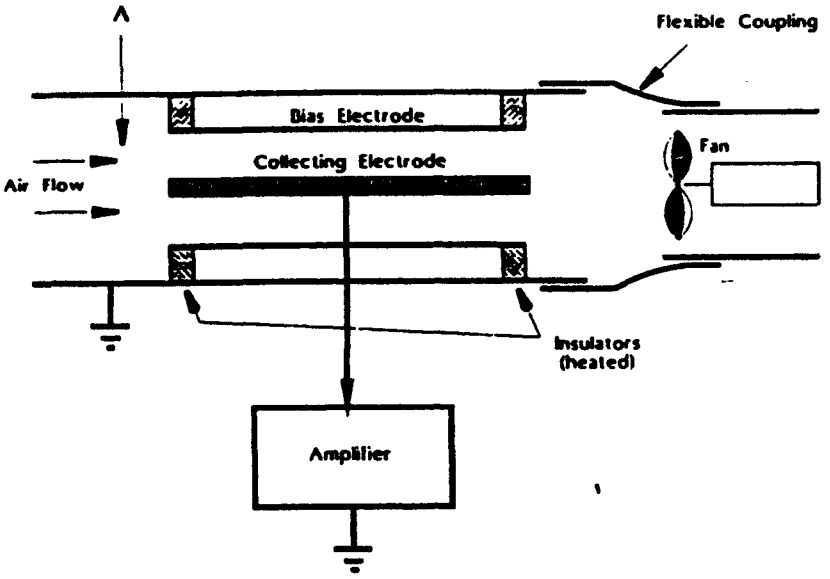

Figure 3. Schematic diagram of a photoionization detector (PID). The position of the ultraviolet lamp is indicated by A.

Prototype TIP-SJ detectors were used for the Concentration Fluctuation Modeling of Chemical Hazards field tests conducted at DPG in September 1991 (Biltoft, 1991), November 1992, and May 1993 (Biltoft, 1993). These field trials provided fast-response concentration measurements for studies of the evolution of the concentration field in a diffusing plume (Yee et al., 1993a and b). A disadvantage of the TIP-SJ is calibration drift when the instrument is exposed to rapid temperature changes. This drift requires a zero-adjustment during operation or compensation during data reduction.

A second recent development in PID technology is the Ultraviolet Ion Collector (UVIC), which is a derivative of the ion collector developed at CBDE-Porton (Jones, 1977). (The UVIC is now commercially available through Enviro Systems, Ltd., Cheshire, England.) The prototype UVIC shown in Figure 2 with a FID inserted in its intake tube features a concentric cylindrical design with a fan at the rear that pulls sample air through a chamber illuminated by a 10.6-eV lamp. With a flow rate of approximately 35 L/min, the UVIC achieves a sensitivity of several parts per billion. A patented "antifouling" design permits UVIC operation over a wide range of contaminant concentrations with a response time greater than 4 Hz. The UVIC weighs 3.5 kg and can be hand carried or tripod mounted. UVIC output can be displayed on the instrument, downloaded to a PC, or fed into a low-power radio telemetry system. The antifouling design and high flow rate minimize baseline drift and hysteresis effects.

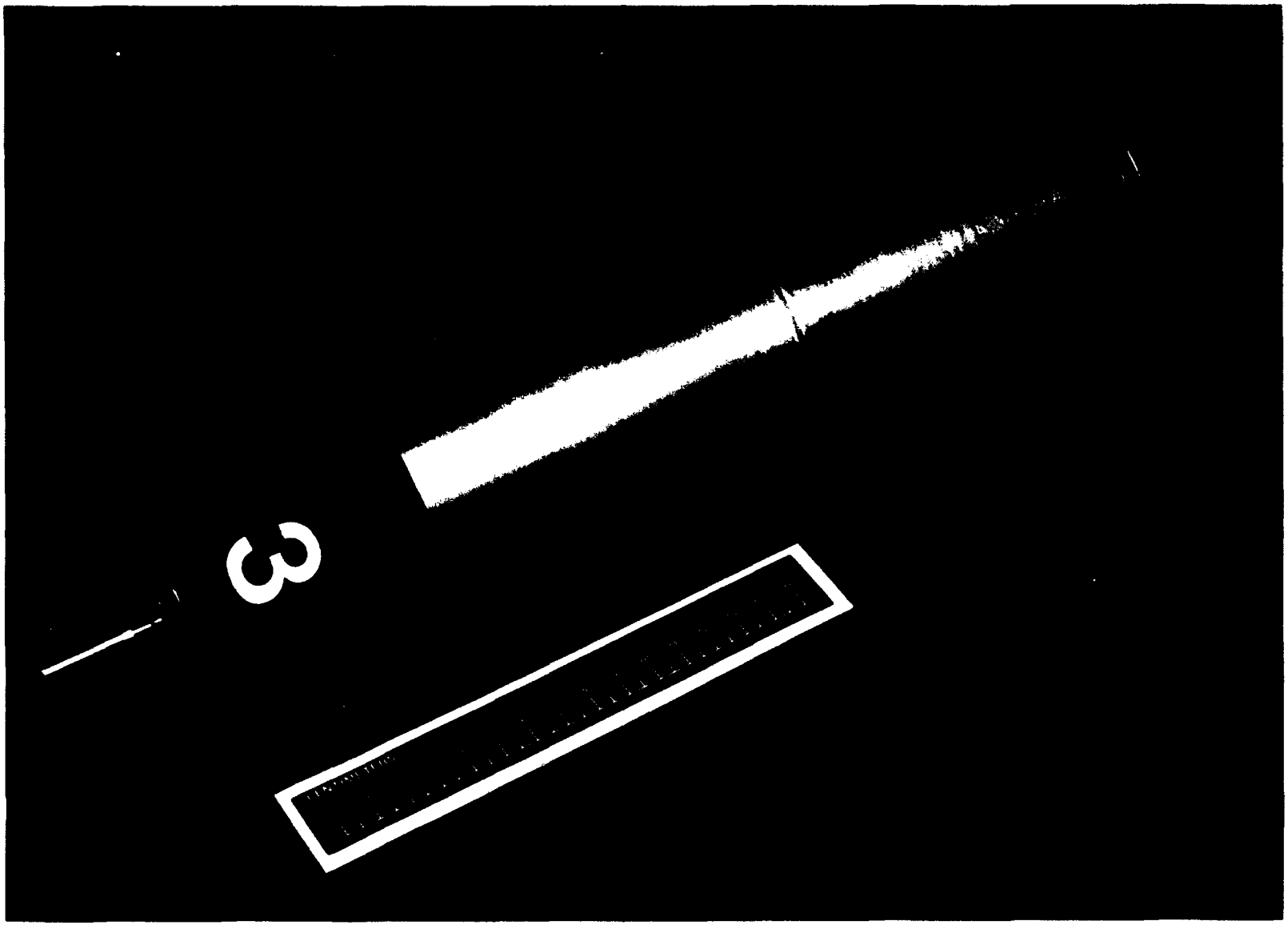

Figure 4. Photograph of the TIP-SJ2 photoionization detector. (Photograph by the U.S. Army Dugway Proving Ground Technical Systems Branch.)

2.6 FLOW AND TURBULENCE INSTRUMENTS

Air flow and turbulence measurements within an enclosed space are typically made using a constant temperature anemometer (CTA) system. A CTA relates the variations of thermal loss experienced by a heated resistance sensor to variations of flow across the sensor. If temperature and pressure are held constant, the heat loss experienced by a sensor (parameterized by the Nusselt number Nu) is approximately proportional to the flow velocity (parameterized by the Reynolds number Re). This relationship is

$$Nu = A + B\,Re^{p}, \tag{2-9}$$

where A and B are empirical constants and p is a velocity-dependent exponent varying from 0.45 to 0.51.

As shown by the schematic diagram in Figure 5, the major components of a CTA system are a heated sensor, Wheatstone bridge, and servo amplifier plus a control and data acquisition system. When the Wheatstone bridge is in balance, the sensor remains at constant temperature and its resistance at that temperature creates a null voltage between amplifier inputs. A change in flow causes the sensor to warm or cool, creating a resistance change that produces a non-zero voltage difference across the amplifier. To re-establish a null voltage, the amplifier applies a measured voltage to the bridge until the sensor equilibrium temperature is restored. System response is governed by servo system gain and amplifier response. A typical CTA sensor is a 5-μm tungsten wire which, with an appropriate amplifier circuit, provides a system response of up to several thousand Hertz. CTA sensors come in many configurations, including single-wire, multi-wire, and omnidirectional (thin film) probes, each designed for specific flow measurement applications. Because each exposed wire responds to the flow component normal to it, multi-wire probes are needed to measure flow velocity components, gradients, and/or rotation. Very low velocity measurements (down to 5 cm/s) are possible using a spherical omnidirectional probe such as the Dantec, Inc. 54N Low Velocity Flow Analyzer. However, the time constant for very low velocity measurements is on the order of 1 Hz, which may be insufficient for indoor turbulence characterization.

As discussed in the next section, CTA measurements were made at the Tower Grid CP using two probes, each consisting of a 5-μm diameter tungsten wire strung across the tips of jewelers broaches. Each probe had a center active region of 1 mm in length and was capable of resolving flows of 20 cm/s or greater at a user-selected rate of up to 100 kHz. A more complete description of this probe is provided by Klewicki and Falco (1990).

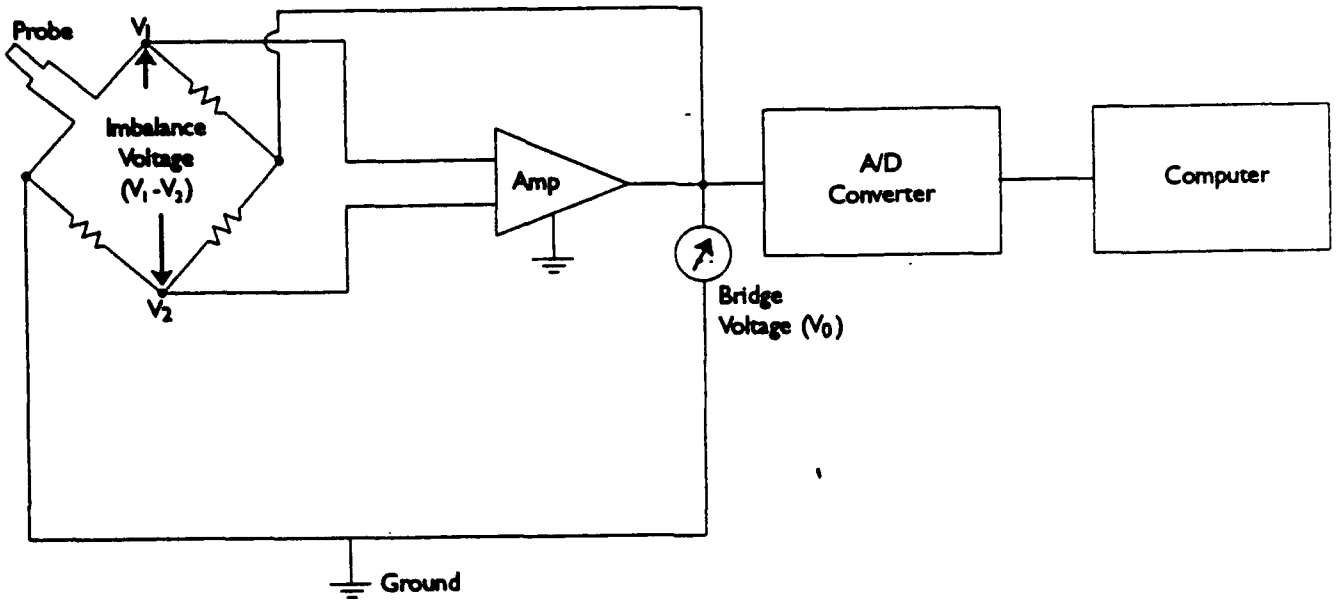

Figure 5. Schematic diagram of a constant temperature anemometer (CTA) system.

2.7 TOWER GRID CP TRIALS

A series of trials were conducted in and around the DPG Tower Grid CP building during May and September 1993 to test the applicability of fast-response flow and contaminant concentration measurement systems to enclosure studies. As shown in Figure 6, the CP building is a single-story, two-room cinder block structure with poorly sealed metal doors and single-pane metal casement windows. The CP building was chosen as a subject for study mainly for convenience; it is usually unoccupied and is located near the test grid where concentration fluctuation trials (Biltoft, 1993) were being conducted.

Tracer concentration measurements were made at the Tower Grid CP building using CBDE prototype UVICs operated by Dr. Helen Higson of UMIST. (Dr. Higson was visiting DPG as part of a British contingent participating in the May 1993 Concentration Fluctuation Trials.) The UVICs were configured for a series of building infiltration trials and puff releases within the building interior. Propylene was used as the tracer. During the infiltration trials, tripod-mounted UVICs were placed beside each exterior wall of the CP building (Units 1, 4, 6, and 7 in Figure 7). With the exception of Unit 5, all UVICs were mounted at a height of 1 m above the surface. Unit 5 was tripod-mounted at 2-m above the CP building roof. Units 2, 3, and 8 were located within the CP building at the positions shown in Figure 7. Each CP infiltration trial consisted of a 30-min propylene release from a single point source positioned

trial propylene dissemination rates and meteorological conditions. The trial results are discussed in Section 2.8.

Figure 8 shows the experimental configuration for the interior puff releases. UVICs were mounted 1 m above the floor on tripods at the locations in the storage room indicated in Figure 8. Each puff release within the CP building was accomplished by bursting a balloon filled with a 2-percent propylene-in-nitrogen mixture at the door between the CP control room and storage area (see Figure 8). The door to the storage area was then quickly closed, and propylene concentrations were measured by the tripod-mounted UVICs in the storage area. The storage area volume is approximately 270 m^3, and each balloon contained approximately 0.1 L of propylene. Thus, a concentration of 0.37 parts per million (ppm) should have been measured at each detector if the propylene was uniformly mixed within the room. Table 2 summarizes the propylene releases and exterior meteorological conditions during the Tower Grid CP puff trials. The puff trial results are discussed in Section 2.8.

Figure 9 shows the experimental configuration for the Tower Grid CP building interior flow and turbulence measurements. The Tower Grid CP flow and turbulence trials were conducted on 23 September 1993 using the hot-wire (CTA) anemometer system developed by the University of Utah Mechanical Engineering Department (See Section 2.6). Measurements were made using two single-wire probes mounted 1.5 m above the floor. The first probe (S1) was located approximately 1 m inside a south-facing window for Trials F1, F2, and F4. The window was open about 2 cm at its bottom. For Trial F3, this probe was moved to the southwest corner of the room at a height of 0.6 m above the floor and approximately 1 m from the south wall and furnace. (The furnace was not in operation during the flow and turbulence trials, but its chimney provided an opening through the roof of the CP building.) The second probe (S2) was placed in the middle of the CP Building storage area. With the exception of Trial F4, the single-wire probes were oriented vertically to optimize sampling of horizontal air motions. During Trial F4, the probe near the window was mounted horizontally to optimize sampling of the vertical wind component. Table 3 summarizes conditions during the interior flow and turbulence trials. The results of these trials are discussed in Section 2.8.

2.8 INTERPRETATION OF CP TEST RESULTS

Table 4 summarizes the hot-wire anemometer measurements made at the Tower Grid CP building on 23 September 1993 (Klewicki et al., 1993). The data in Table 4 show mean velocities on the order of 1 cm/s or less, well below the probe velocity measurement threshold (nominally 20 cm/s). These mean velocities indicate the total absence of a well-defined flow direction. Other than indicating the absence of a well-defined flow, no significance should be attached to the magnitudes of the mean velocities.

The root mean square (RMS) fluctuations about the mean velocities in Table 4 are of greater significance than the means because they are measures of the turbulence levels at the various positions within the room. The relatively high RMS values obtained during Trial F1 are attributable to people standing and walking within the room during this trial. As shown by Table 4

Figure 6. The Tower Grid Command Post (CP) at Dugway Proving Ground. (Photograph by the U.S. Army Dugway Proving Ground Technical Systems Branch.)

Table 1. Summary of Propylene Dissemination and Meteorological Conditions During the Tower Grid CP Infiltration Trials.

Trial No.	1993 Date/Time (UTC)	Dissemination Rate (L/min)	Wind Direction (Deg)	Wind Speed (m/s)	Ambient Temperature (°C)
I1	20 May/1935	30	210	4	30
I2	24 May/1534	60	190	3	23
I3	24 May/1637	70	190	1.5	28

Table 2. Summary of Propylene Releases and Exterior Meteorological Conditions During the Tower Grid CP Puff Trials.

Trial No.	1993 Date/Time (UTC)	Propylene Disseminated (L)	Wind Direction (Deg)	Wind Speed (m/s)	Ambient Temperature (°C)
P1	24 May/1830	0.10	220	1.7	29
P2	24 May/1939	0.12	240	1.4	32

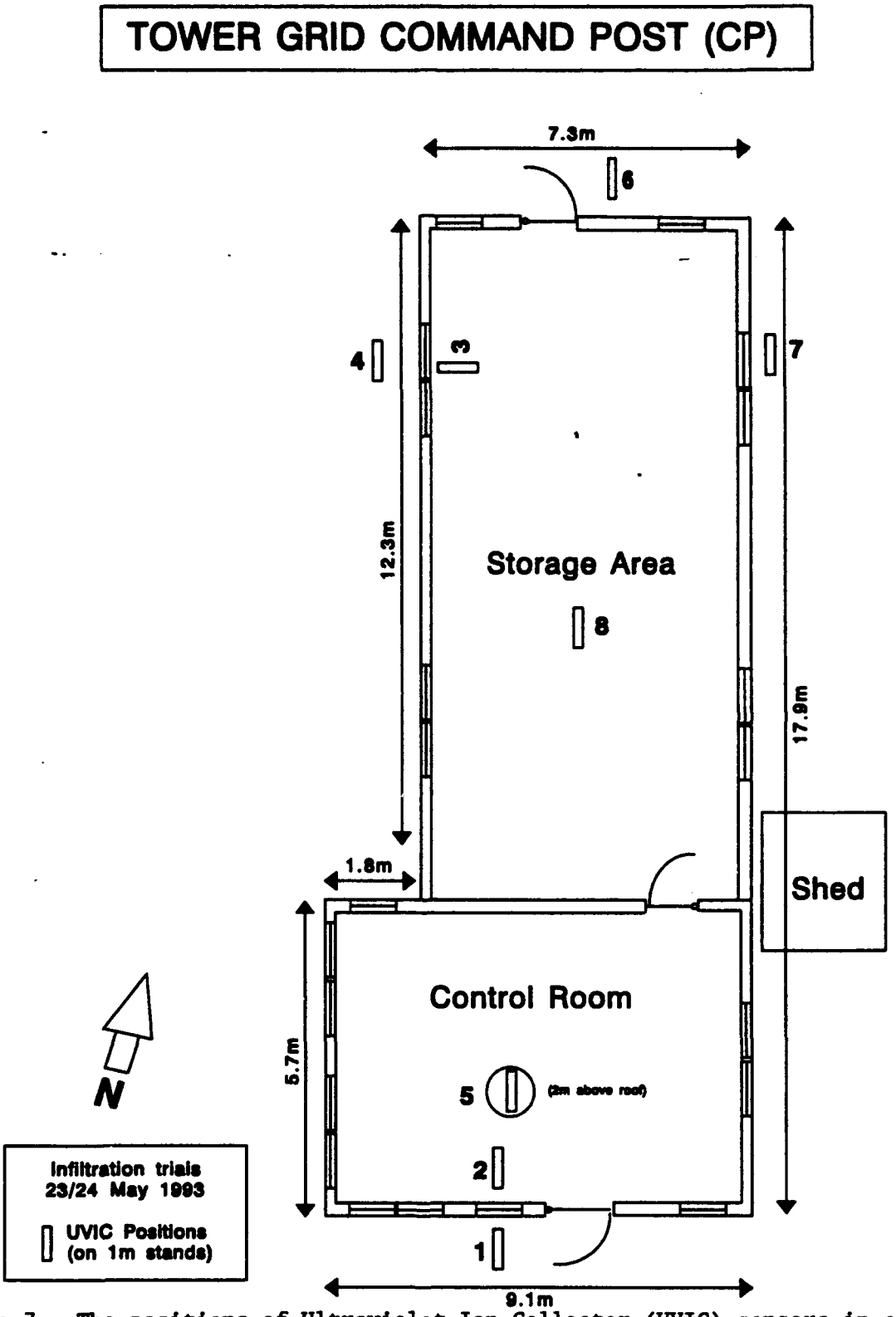

Figure 7. The positions of Ultraviolet Ion Collector (UVIC) sensors in and around the Tower Grid CP building during the May 1993 building infiltration trials.

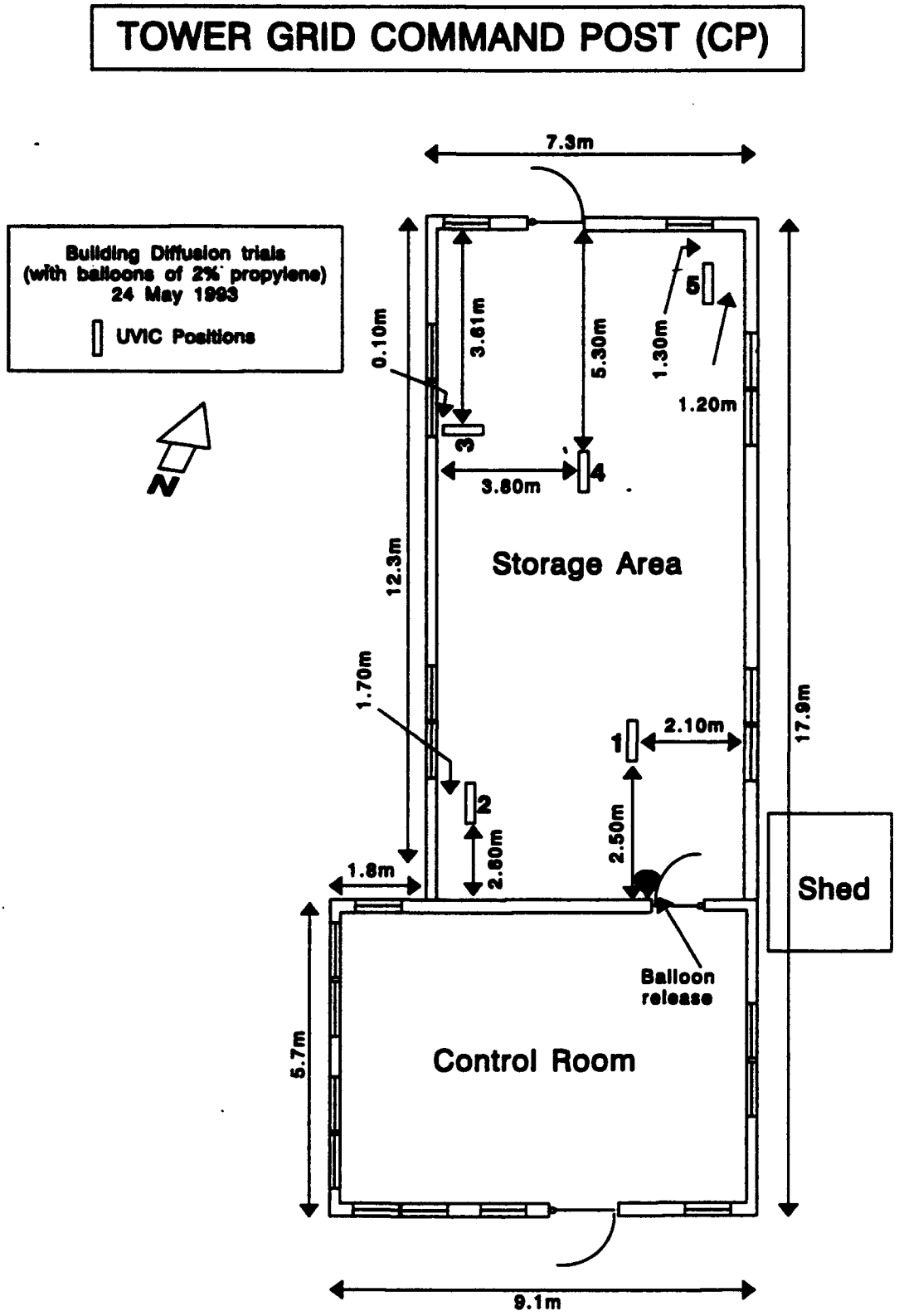

Figure 8. The positions of Ultraviolet Ion Collector (UVIC) sensors in the Tower Grid CP building storage area during the May 1993 indoor puff release trials.

Table 3. Tower Grid CP Interior Flow and Turbulence Trial Summaries.

Trial No.	1993 Date/Time (UTC)	CTA Wire Orientation	Indoor Temperature		Barometric Pressure (kPa)
			Center (°C)	Window (°C)	
F1	23 Sep/1611	Vertical	20.3	20.6	866.8
F2	23 Sep/1630	Vertical	21.1	19.7	867.1
F3	23 Sep/1718	Vertical	20.7	19.7	867.0
F4	23 Sep/1745	Horizontal	20.7	20.4	867.0

Table 4. Summary of the Hot-Wire Anemometer Measurements Made at the Tower Grid CP Building on 23 September 1993 (Courtesy of Klewicki, Kelner, and Murray, 1993).

Trial	Sample Rate (Hz)	Sample Size ($\times 10^3$)	Probe	Flow Velocity (m/s)	
				Mean	RMS
F1	100	100	S1	-0.0165	0.0185
	100	100	S2	-0.0027	0.0146
F2[a]	100	100	S1	0.0058	0.0314
F3	100	100	S1	-0.0163	0.0128
	100	100	S2	0.0015	0.0010
F4	100	100	S1	0.0147	0.0783
	100	100	S2	0.0013	0.0033

[a] No data were obtained for probe S2 during Trial F2.

this motion increased the turbulence level in the room by a factor of 5 to 10 over the turbulence obtained when the room was unoccupied (Trials F3 and F4). The fact that the probe 1 RMS value exceeded the probe 2 RMS value during Trial F3 may be explained either by the furnace chimney drawing air out of the room or by convection near the wall. When probe s1 was oriented to intercept the vertical velocity (Trial F4), it measured the largest velocity fluctuations, indicating that the air distribution within the room was dominated by vertical rather than horizontal motions.

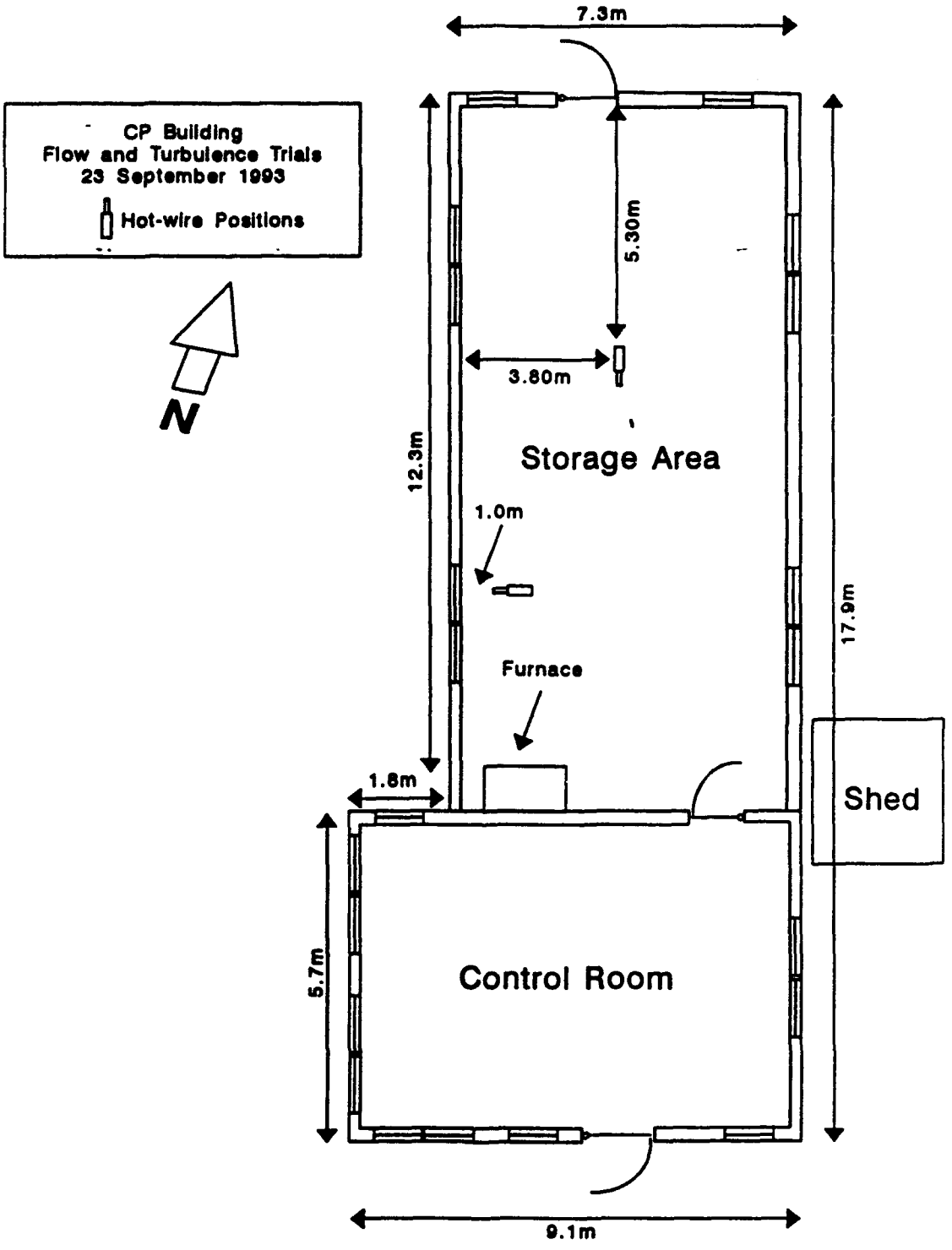

Figure 9. The positions of hot-wire anemometer probes in the Tower Grid CP building storage area during the 23 September 1993 flow and turbulence trials.

The hot-wire anemometer flow measurements summarized in Table 4 demonstrate the efficacy of using these instruments within enclosures. When positioned properly, hot-wire anemometers can distinguish the subtle differences in indoor flow and turbulence levels that are needed to characterize air and contaminant distributions within enclosures.

The infiltration trials included the continuous release of propylene over 30-min periods from a point source stationed upwind of the front of the Tower Grid CP building control room. Because of the light and variable winds during the infiltration trials, the propylene plume intermittently impacted various parts of the building exterior. The highest concentrations were registered by UVIC #7 located near the northeast corner of the CP. Impactions against the front of the building were registered by UVIC #1. UVIC #2, located just inside the window from UVIC #1, sampled infiltration through the south side of the CP control room. (UVIC positions during the infiltration trials are illustrated in Figure 7.)

Figure 10 shows time series concentration plots for the first 15 min of infiltration Trial 12 for UVICs #1 and #2. Concentration peaks from UVIC #1 indicating plume impaction against the south face of the CP control room are mirrored by peaks from UVIC #2, but with a time delay of 45 s and considerable attenuation of both the peak concentration and intermittency (zero concentration) periods. The building was therefore acting as a smoothing filter on the plume concentration field. Figure 10 also illustrates a slow increase in the UVIC #2 concentration baseline to a magnitude of 1 ppm, indicating that the control room was also slowly accumulating the infiltrating propylene.

Very little infiltrating gas was observed in the CP building storage area in spite of the fact that UVIC #7 registered the highest propylene concentrations of all exterior sensors. Because the signals from UVIC #8 were too noisy for analysis, the only measurements available for the storage area are from UVIC #3, stationed just inside the window from UVIC #4. Small rises in propylene concentration (on the order of 0.2 to 0.3 ppm) were observed approximately 60 s after concentration peaks were observed by UVIC #4. However, the propylene baseline remained at or below 0.1 ppm and did not rise as it did in the control room. Either the storage area propylene concentrations were inadequately sampled during these trials, or the force of the wind against the south side of the CP building contributed to the higher concentrations infiltrating into the control room.

As discussed in Section 2.7, the puff disseminations within the Tower Grid CP storage area were accomplished by bursting balloons filled with a 2-percent propylene-in-nitrogen mixture between the control room and storage area. This door was then closed to allow the propylene to diffuse within the storage area without additional mixing with air from the control room. There was no forced convection in the storage area during these trials, but the furnace located in the southwest corner of the storage area (shown on Figure 9) had an open chimney that could have drawn warm air from the storage area interior. Sunlight also heated the wall and windows along the west side of the building, possibly causing a slow convective circulation within the storage area.

Of the five UVICs available for the puff release trials, three were positioned near walls to intercept convective currents and two (UVICs #1 and #4) were placed closer to the center of the room (i.e., further from the influence of convection). UVIC #2 was located near the storage area southwest window and UVIC #3 was located near the northwest window. Both of these positions received full sun and most likely experienced upward convective motions. UVIC #5, located near the northeast window, was in the coolest part of the storage area where downward convective motions might be expected. Puff trial UVIC positions are shown on Figure 8. Because UVIC #4 did not function properly during the balloon trials, the gas concentration measurements near the center of the storage area limited to UVIC #1.

The propylene cloud was first detected in large concentrations (approaching 12 ppm) at UVIC #2 45 s after balloon burst. As time progressed, the concentration levels at this position slowly decreased to a fairly constant level of 1 ppm, as shown on Figure 11. Although UVIC #1 was located only 2.5 m from the point of balloon burst, the propylene cloud required 75 s to reach it. The concentration peaks at UVIC #1 were also much lower than at UVIC #2, indicating that convection probably drew the cloud towards the west wall of the storage area.

The propylene cloud was first observed at the far corners of the room (represented by the UVIC #5 plot in Figure 11) 3 to 3.5 min after balloon burst. After experiencing slightly elevated initial concentrations for the first few minutes of exposure, the propylene concentration level decreased to a value near 1 ppm. All functioning UVICs experienced a nearly uniform 1 ppm concentration 10 to 12 min after balloon burst, indicating that near-uniform mixing had been achieved by this time. Towards the end of each trial, the concentration baseline decayed slowly as the tracer escaped from the building.

While not fully defining all the characteristics of contaminant distribution within the Tower Grid CP, the infiltration and puff trials demonstrated the efficacy of using fast-response concentration PID technology for indoor contaminant distribution studies. These trials also illustrated the high concentration levels that can occur with initial introduction of a contaminant into an enclosure, followed by convective movement and dispersion of the contaminant through the enclosure. Another interesting feature of the tracer concentration-time profiles is the absence of intermittency once the contaminant arrived at a sampler position, suggesting that puff or plume concentration intermittencies observed in the ambient atmosphere are caused by scales of turbulence not found within enclosures. UVIC prototype flow rates of 35 L/min are somewhat high for indoor applications and may have contributed to the uniform mixing observed in the latter half of the trials. PID detectors with substantially lower flow rates can be designed for indoor contaminant distribution studies.

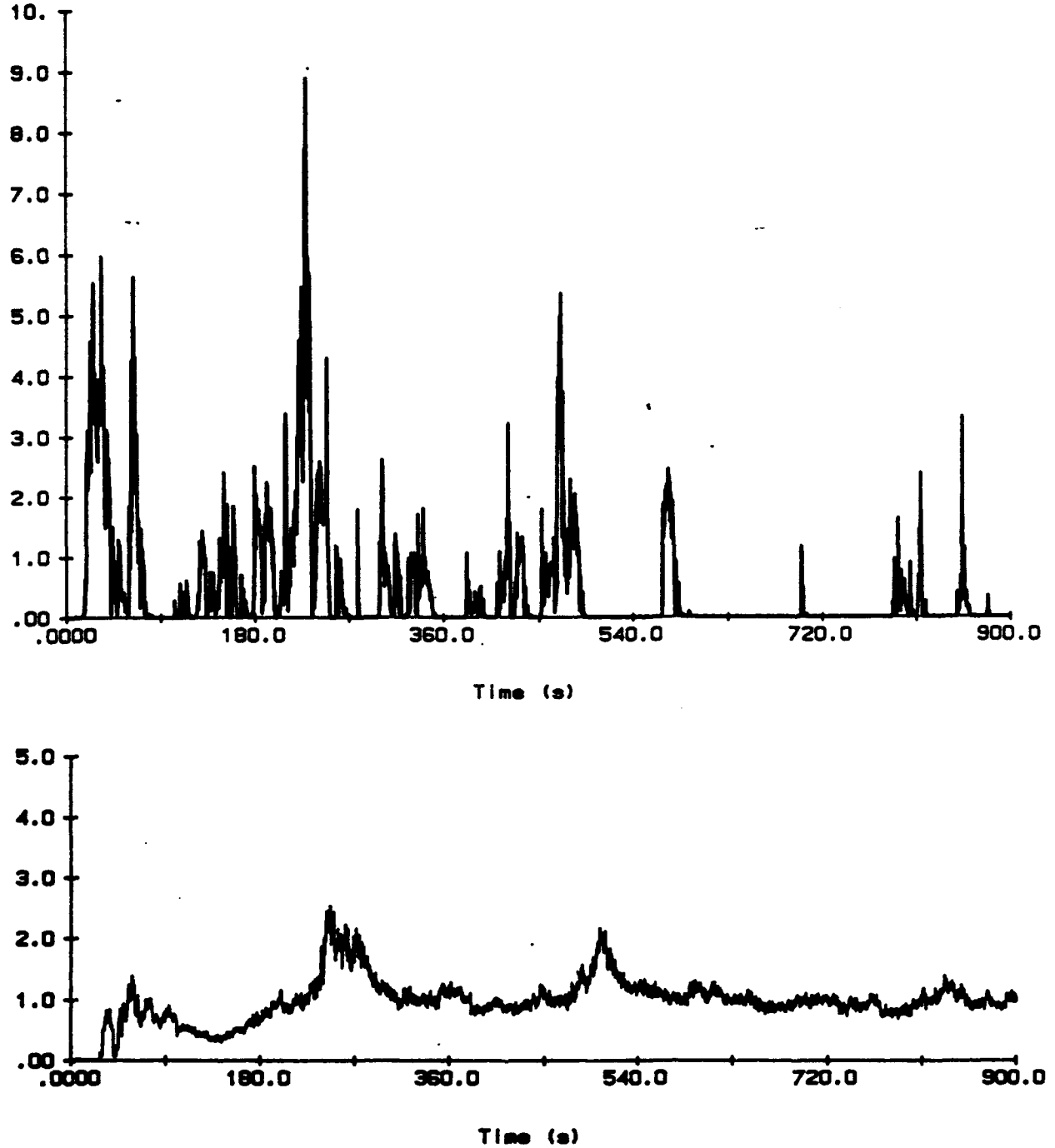

Figure 10. Concentrations of propylene gas in parts per million (ppm) sampled by UVIC #1 (upper half) outside the front of the Tower Grid CP building and UVIC #2 (lower half) inside the CP building control room. The time scale is in seconds from the beginning of Trial 12 dissemination. (Plots courtesy of UMIST Department of Chemical Engineering.)

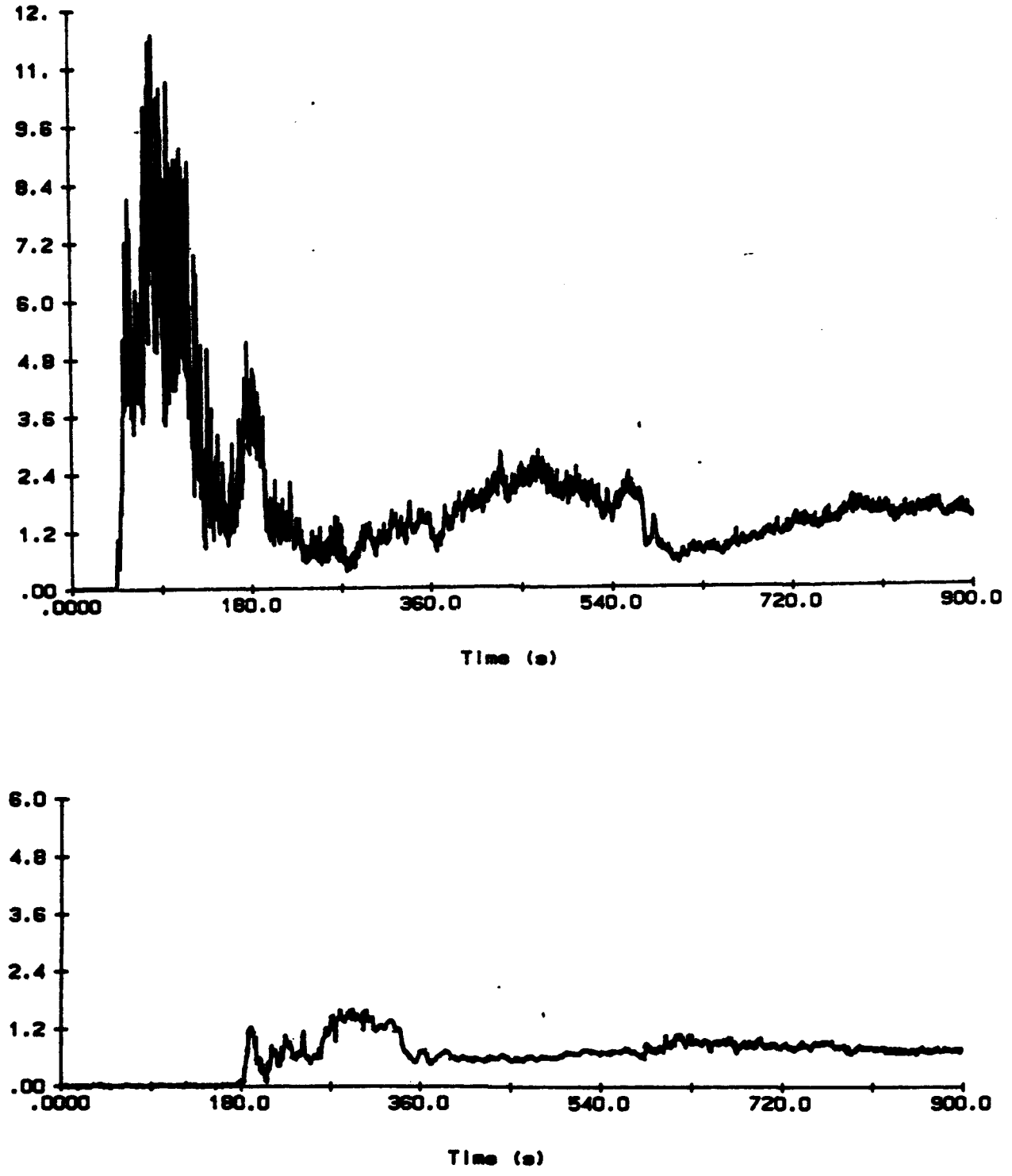

Figure 11. Concentrations of propylene gas in ppm sampled by UVIC #2 (upper half) and UVIC #5 (lower half) in the CP building storage area during Trial P2. The time scale is in seconds beginning at balloon burst. (Plots courtesy of UMIST Department of Chemical Engineering.)

SECTION 3. APPENDICES

APPENDIX A. METHODOLOGY INVESTIGATION PROPOSAL AND DIRECTIVE

DEPARTMENT OF THE ARMY
U. S. ARMY DUGWAY PROVING GROUND
DUGWAY, UTAH 84022-5000

REPLY TO ATTENTION OF

AMSTE-TC-D (70-10p)

MEMORANDUM FOR Commander, U.S. Army Dugway Proving Ground, ATTN: STEDP-MT-A, Dugway Proving Ground, UT 84022-5202

SUBJECT: Test Execution Directive, Test Technology Development Program

1. Reference TECOM Regulation 70-15, 16 Sep 91, Research, Development, and Acquisition - TECOM Test Technology Program.

2. This memorandum authorizes the execution of the projects listed in enclosure 1 under the TECOM Test Technology Development program. Detailed project descriptions listed in the FY93 TDAP database are the basis for headquarters approval of the projects.

3. Upon receipt of this directive, review TRMS II database test milestone schedules established for the projects and enter any necessary reschedules directly into the TRMS database with appropriate justifying narrative.

4. All safety, health, energy, and environmental issues associated with the project will be considered and necessary documentation or support studies/information/approvals required will be accomplished/prepared prior to project initiation. Security/OPSEC requirements will be adhered to.

5. All reporting, including final technical reports prepared by contractors, will be in accordance with the requirements and appropriate formats as specified in the references. Final reports will be reviewed and approved by Headquarters, TECOM, Directorate for Technology.

6. FY93 RDTE funds authorized for the projects are listed on enclosure 1. GOA Form 1006 will be forwarded by the TECOM Directorate for Resource Management, and will be updated to reflect all changes to current program. A cost estimate is to be submitted within 30 days following receipt of this directive.

8 [illegible] 199[illegible]

AMSTE-TC-D
SUBJECT: Test Execution Directive, Test Technology Development Program

7. Point of contact at this headquarters is Ms. Cyndie McMullen, AMSTE-TC, amstetcd@apg-9.apg.army.mil, DSN 298-7881/7884.

FOR THE COMMANDER:

Encl

FREDERICK D. MABANTA
Chief, Technology Development Division
Directorate for Technology

CF:
Cdr, USADPG, ATTN: STEDP-MT-AT (Perry Pederson)

APPENDIX B. REFERENCES

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